

Chapter 5

Portable Energy and Propulsion Technologies

To provide locomotion for transport vehicles involves the availability of two inter-dependent components: (1) A portable fuel (stored chemical energy) or a portable energy source in the form of a battery (stored electrical or flywheel energy); and (2) an engine or motor that consumes stored portable energy and converts it into mechanical motion. Various portable fuels and energy storage devices have been developed in the last century, the champion fuel being petrol because of its low cost and availability, and the champion battery being the lead-acid device because of its ruggedness and recharge ability. Engines can be divided into three categories: (I) internal combustion engines (ICEs) fed by portable chemical fuels that can react with oxygen in the air, (II) motors driven by the electricity from chemical or mechanical storage batteries, and (III) fuel-cell engines (FCEs) fed by chemical fuels that react with atmospheric oxygen. ICEs in category (I) can convert the heat of fuel combustion into mechanical motion via piston action with an efficiency of 30–40%, while motors in category (II) can convert electricity from a storage battery via induction into mechanical motion of the wheels of an automobile via a gear-train with an efficiency of 85–95%. FCEs in category (III) utilize an electrochemical reaction between atmospheric oxygen and a fuel that takes place on special electrodes with an efficiency between 45% and 85%. The generated electricity then drives a motor as in (II). The quoted efficiencies are ratios of delivered energy of mechanical motion divided by energy extracted from a fuel or battery. Although FCEs are more efficient than ICEs, because of problems discussed below, the ICE has so far won out in the automotive field. It is presently the most developed device for propelling cars. Motors driven by batteries alone have also lost out against ICEs because of driving range limitations discussed below. In what follows, we first review portable fuels and energy holding batteries, and then discuss ICEs and FCEs.

5.1 Review of Portable Fuels and Other Energy Carriers

Portable fuels and portable batteries can be grouped as follows:

- (a) Natural non-renewable fuels:
 - Oil (liquid hydrocarbons – $C_m H_n$)
 - Compressed natgas (methane, ethane, propane, butane: CH_4 , C_2H_6 , C_3H_8 , C_4H_{10})
 - Coal (C)
- (b) Manufactured energy carriers (synfuels and batteries):
 - Hydrogen (H_2), from water (H_2O) + electricity or heat
 - Ammonia (NH_3) and hydrazine (N_2H_4), from water (H_2O) + air (80% N_2) + electricity or heat
 - Syn-petrols and methane ($C_m H_n (O_k)$, CH_4), from water (H_2O) + coal (C) + electricity or heat
 - Methanol (CH_3OH), ethanol (C_2H_5OH), from biomass (e.g. corn) + sunshine + electricity
 - Rechargeable electric storage batteries; rechargeable mechanical flywheel batteries; rechargeable super capacitors

As long as large quantities of energy can not be transmitted wirelessly (Tesla's dream), there will always be a need for portable energy sources. At present, portable fuels used in land or sea transportation and in aircraft propulsion come mostly from the non-renewable resources listed under (a), that is: Oil (petrol or diesel), Natural Gas (liquefied or compressed), and Coal. When these non-renewable resources are depleted, artificially manufactured energy sources must be developed which can be carried on-board vehicles to fuel engines or energize motors that propel the vehicles. Such portable energy can come in the form of a portable (synthetic) fuel that can be refilled periodically into an on-board fuel tank, or as an energy storage battery which is periodically recharged. In what follows we briefly examine past and present activities to develop portable synthetic fuels and rechargeable energy storage devices.

5.1.1 Portable Synfuels

The only practical solution to the out-of-oil problem is to manufacture portable fuels in which power-plant heat or electricity is converted (with some loss) and stored as chemical energy in an oxidizable compound. Such portable synfuels are most economic if they can react chemically with atmospheric oxygen (O_2) to produce heat or electricity and thence propulsion. Preferably they are synthesized from water (H_2O) and air (80% N_2 ; 20% O_2), both of which are abundantly available on earth. Hydrogen (H_2) synfuel would be advantageous since it can be made from water and returned into water when consumed, without polluting the atmosphere. It can be burnt in internal combustion engines (ICE) producing heat and propulsion, or consumed by a fuel-cell engine (FCE) to propel a car. A problem with gaseous H_2 is its high storage volume, the main reason why it is not widely used as a clean fuel for ICEs to replace "dirty" petrol.

Compact electrochemical fuel-cells have been developed that consume tank-supplied hydrogen (H_2) and air-supplied oxygen (O_2), which can make sufficient DC electricity at near-ambient temperatures to power a car (see [Section 5.2.2](#)). Electric motors to turn wheels with this electricity are well-developed today and hybrid fuel-cell-driven automobiles may be coming on the market after some basic problems are solved. Fuel-cell engines running on pure hydrogen, exhaust only water (H_2O). No nitric oxides (NO_x) nor carbon dioxide (CO_2) are emitted because they operate at lower temperatures than those of combustion engines. Thus fuel-cells are ideal car engines that do not pollute the environment. Interests of environmentalists and future-world planners have coincided here to promote this power source for (future) autos and trucks. As discussed in the next chapter, there are still problems to be solved for fuel-cells. One major problem is the fact that hydrogen gas is difficult to store compactly. Nevertheless hydrogen (H_2) is a potential universal synfuel, producible from water by electricity or heat (provided by nuclear, coal, or other prime energy source), since it can empower ICEs and FCEs without CO_2 air-pollution.

Besides hydrogen (H_2), other potential portable synthetic fuels which can be made from atmospheric nitrogen (N_2) and water (H_2O) as feeds, are hydrazine (N_2H_4) or ammonia (NH_3). Hydrazine is a liquid, and ammonia is liquid when compressed at a very modest pressure of 12 atm. Both have chemical energy stored in them comparable to petrol, and both produce heat in a combustion engine or can generate electricity via a fuel-cell when reacted with oxygen (O_2) from the air. Hydrazine is presently used as a rocket fuel, while liquefied ammonia is used as a fertilizer in agriculture. An experimental ammonia-burning ICE was successfully tested some time ago in The Netherlands at Delft University. More recently HEC (Hydrogen Engine Center), founded by entrepreneur Ted Hollinger in Iowa, is manufacturing and selling ammonia-fueled ICEs for tractors and farm equipment. If it is found difficult in the future to fly airplanes with pure hydrogen as fuel, a possible alternative might be to use hydrazine or ammonia as a fuel, if this can be done without significant air pollution. Should byproduct NO_x gases be present due to high-temperature combustion of hydrazine or ammonia, their conversion to O_2 and N_2 by catalytic devices used in many of today's automobiles must be considered. In colder fuel-cells, NO_x exhausts from hydrazine and ammonia fuels are virtually absent. That is FCEs yield essentially pure N_2 and H_2O as exhausts. The advantage of ammonia and hydrazine is that these synfuels are much easier to store than hydrogen. Ammonia is as stable as natgas, but hydrazine decomposes when slightly heated. The latter may be stabilized when hydrated and/or loosely bonded to a complex. Though pure hydrogen is preferred for running fuel-cells, ammonia and hydrazine can be catalytically decomposed to hydrogen and nitrogen on FCE electrodes by alloys of platinum, ruthenium, osmium, and iridium. Because of easier tank storage of ammonia, it may be preferred over hydrogen for automobile FCEs, even though the required catalytic decomposition of ammonia on FCE membranes is a complication that consumes extra energy. New high-temperature solid oxide fuel cells (SOFs) can use ammonia directly however (Refs. III-8 through III-11).

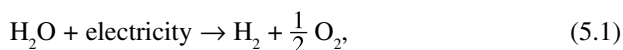
It was reported recently that nitrogen (N_2) can be compressed into a solid of pure trivalent N, storing lots of chemical energy. In an ICE device its decomposition could be detonated by an electric spark. The exhaust would be harmless N_2 already present in our atmosphere at 80%. Synthesizing this nitrogen compound requires $1,725^\circ\text{C}$ and 10^6 atm of pressure however so it is doubtful it will ever be used as a portable synfuel.

Synthetic portable liquid hydrocarbons can be made from coal (C), water (H_2O), and electricity by the Fischer–Tropsch process, yielding man-made petrol-like compounds (C_mH_n and $C_mH_nO_k$). This was, and still is done in South-Africa at its SASOL plant which was built during WW-II by the US Kellogg company. Because of war-related blockades and perils of ocean-crossing petroleum transports, South-Africa ran short of petrol in WW-II, so synthetic SASOL petrol became economically attractive. Coal-derived SASOL synfuels, if massively consumed in combustion engines, do produce globe-warming carbon dioxide (CO_2) gas however. They are not carbon-neutral like bio-alcohols. In a future pollution-intolerant society the use of SASOL-produced petro-chemicals might therefore be restricted to non-automobile applications such as plastics manufacture. However during the interim period between the end of the petroleum era and the start of a uranium millennium, it may be necessary to make synthetic petroleum fuels by SASOL techniques to keep our long-haul transport fleets rolling, moving, and flying.

Extracting liquid alcohol (C_2H_5OH) and methanol (CH_3OH) from cultivated corn or other suitable plants or algae is another scheme to make hydrocarbon synfuels. Growing corn requires sunshine and electric power for fertilizer production and farm operations. Thus the combined prime energies of power-grid electricity and sunshine are converted into portable fuel. Since the same amount of CO_2 gas is returned to the biosphere in combustion as was taken in by plants or algae during photosynthesis, there is no net globe-warming biosphere pollution (unlike SASOL). Such biofuels are thus legitimate carbon-neutral synfuels even though they emit carbon-dioxide and require one-third of all lands to grow enough for the total replacement of petro-fuels.

As discussed in [Section 4.1](#), unless (nuclear) electricity is available for agriculture operations and processing, there are insurmountable problems if one considers replacing petrol *only* with bio-alcohol in an out-of-oil economy. Energy budgets for farming, fermenting, distilling, manufacture of farm equipment, etc., show that the input energy to obtain alcohol from corn or sugarcane may exceed the energy present in the final alcohol product. Farming improvements might lower the input/output energy ratio to 80–90%, but it means that in a no-oil, no-nuclear, no-coal economy, 80–90% of agriculturally grown alcohol must be put back into its own operations. Then to power the world's transportation fleets, one would need four times all available land in the world for growing corn, which is of course impossible.

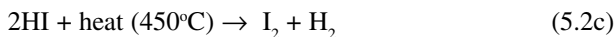
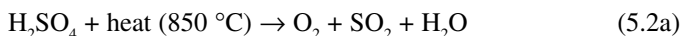
Hydrogen synfuel can be made by electrolysis of water using available grid electricity:



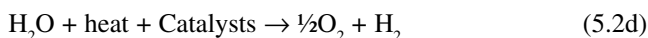
This scheme is reported to produce 7 ft^3 (15.36 g) of very pure H_2 at 2.25 V DC with an input of 1 kWh(e). Iron plates are used for the H_2 electrodes and nickel-plated

steel for the oxygen electrodes (Ref. II-1). Assuming our standard energy equivalence (Brief 4) that 10 kg of H_2 can produce 0.72 GJe of electro-mechanical fuel-cell output energy, one finds that 1 kWh(e) = 0.0036 GJe of electric grid energy can be converted into portable H_2 for fuel-cell electricity generation with an efficiency of $[15.36 \times (0.72 \text{ GJe}/10^4)]/[3.6 \times 10^{-3} \text{ GJe}] = 0.307 = 30.7\%$. Assuming that grid electricity was generated from heat by a steam turbine at 33% efficiency, the overall conversion efficiency of making hydrogen fuel from latent uranium (or coal) energy is then 10%.

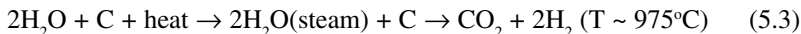
Instead of electrolysis, hydrogen can also be produced using fission heat directly in a “chemo-nuclear” reactor. This skips conversion of nuclear heat to electricity by a steam turbine. For example at 850°C sulfuric acid (H_2SO_4) breaks apart, and with iodine (I_2) it can generate H_2 as follows (Ref. II-10):



or overall:



This “sulfur-iodine” catalyzed scheme using nuclear reactor heat is under investigation, and may be compared with the older “steam-reforming” method of making H_2 (now undesirable because CO_2 is made):



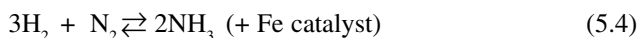
The efficiency of producing H_2 by (5.2) or (5.3) using (nuclear) heat has been estimated to be about 60%, meaning 1 GJ of (nuclear) heat can be converted to 0.6 GJ of H_2 -carried chemical energy.

Before selecting H_2 production by either one of reactions (5.1), (5.2), or (5.3), it is prudent to consider the entire picture of a future “hydrogen economy”. Some questions are: is it most economic to make hydrogen in large quantities at several large conversion plants and to distribute it through pipelines like today’s natural gas for delivery to fueling stations; or is transport in the form of compressed or adsorbed hydrogen by tanker trucks better, as is done today with petrol? Or is it more efficient and practical to employ existing electric grid lines that already distribute power widely, to generate hydrogen by electrolyzing tap-water at city fuel stations equipped with electrolyzers. For fuel-cell usage, H_2 must be quite pure (Section 5.2.2). If contaminated by mercaptans for example, it must be passed through special scrubbers to remove them. Rather than piping H_2 to commercial fuel stations, hydrogen could also be distributed directly to homes using pipe-lines similar to natgas distributions. Then customers can directly fill their H_2 fuel tanks at home. The hydrogen might be adsorbed in an automobile fuel “bladder” (fuel tank of the future?). With a little heat, the bladder releases H_2 again to run the auto’s

fuel-cell. Alternatively, electrolysis of tap water (generating H_2), might be carried out in people's garages at night with grid electricity. Because "slippery" hydrogen effuses through many materials, and embrittles or attacks a number of metals, current natgas pipelines are unsuitable for distributing hydrogen. Thus new (larger) pipelines would have to be installed for the distribution of hydrogen. Another concern with home-provided or home-generated H_2 fuel would be safety, similar (but more stringent) to present-day home delivery of natgas.

Without considering energy expenditures for hydrogen gas distribution, the 60% efficiency of producing hydrogen by (5.2) or (5.3) using nuclear heat means that 1 GJ of latent uranium energy is converted into 0.6 GJ of hydrogen-held chemical energy. This in turn is converted to 0.33 GJ(e) of electro-mechanical energy in a H_2 fuel-cell at 55% efficiency. Since 1 GJ of nuclear heat can also be converted to 0.33 GJ(e) of electricity with steam turbines, portable H_2 produced via (5.2) or (5.3) followed by fuel-cell consumption gives the same overall conversion efficiency of 33%. It puts nuclear fission energy "under the hood of an automobile". In contrast, we found overall energy conversion (5.1) by electrolysis to be only 10% efficient. However additional costs for distributing H_2 from large chemo-nuclear reactor plants by new pipelines or tank-trucks must be added and compared with electric-grid electrolysis of H_2O in individual H_2 -fueling stations to determine total H_2 fuel costs. As mentioned, the advantage of the latter scheme is that wide-spread distribution of electricity by power grids is already in place.

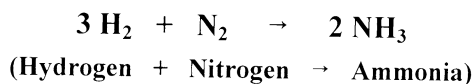
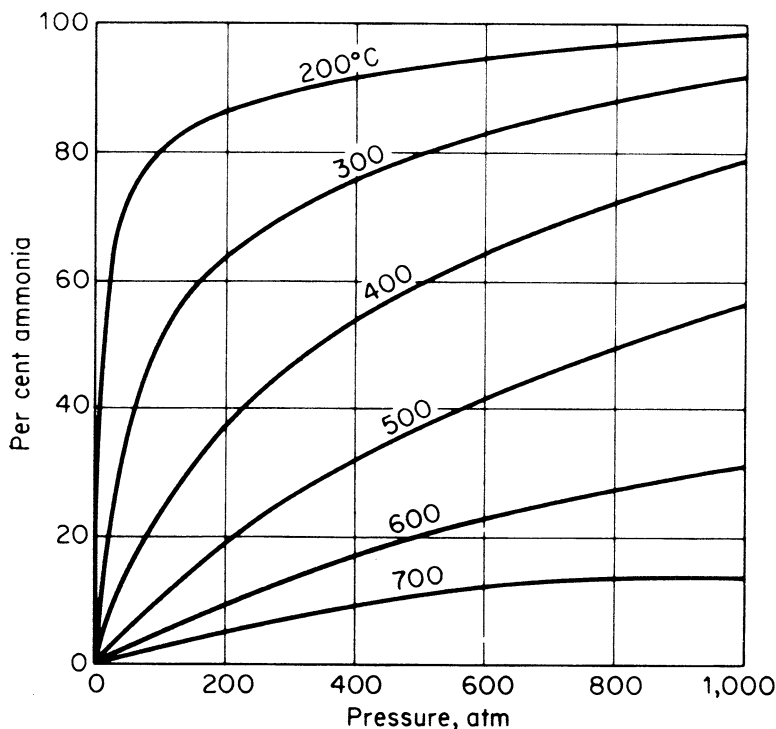
Because of the distribution and storage problems of gaseous hydrogen, after production with (nuclear) electricity as discussed above and before use as a portable fuel in a vehicle, one finds that to remain practical one must either liquefy it or compress it with nitrogen (air) to form liquid ammonia ("second" hydrogen). The latter is made by the Haber-Bosch process (Ref. II-11):



As shown in Brief 13, formation of ammonia (NH_3) in this reversible reaction is favored by high pressures at moderate temperatures. At 272 K ($-0.5^\circ C$), ammonia is a liquid and at room temperature (300 K) it can be stored at a pressure of about 12 atm (Brief 14). This is much easier to handle than compressed H_2 gas at a pressure of 600 atm or liquid H_2 at 20 K for storage in an automobile fuel tank of acceptable dimensions for a 600 km driving range. Liquefying hydrogen to $T = 20$ K requires approximately 77,567 kJ/kg = 155 kJ/mole of H_2 , while compressing it into liquid ammonia via the Haber-Bosch process costs about 4,475 kJ/kg = 80.5 kJ/mole of NH_3 in compressor energy.¹ Since one mole of NH_3 has 1.5 times more H atoms than one mole of H_2 , comparable energies of compression are 76 kJ for liquefaction and 27 kJ for

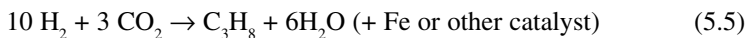
¹In chemistry a mole is defined as a quantity of 6.022×10^{23} molecules or atoms (Avogadro's number). This quantity weighs M grams, equal to the atomic weight M of the molecule or atom. Thus 1 mole of CO_2 molecules = 6.0247×10^{23} CO_2 molecules weighs 44 g ($M = 44$); 1 mole of U-235 atoms = 6.0247×10^{23} U-235 atoms weighs 235 g with $M = 235$.

ammonia synthesis per mole of H atoms. These values compare with $\sim 700,000$ kJ/kgH₂ or ~ 350 kJ/moleH₂ to manufacture hydrogen by electrolysis (Section 5.1.1). Clearly ammonia is less expensive as a portable hydrogen carrier than liquid hydrogen.

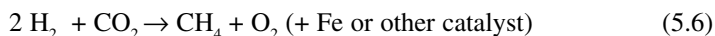


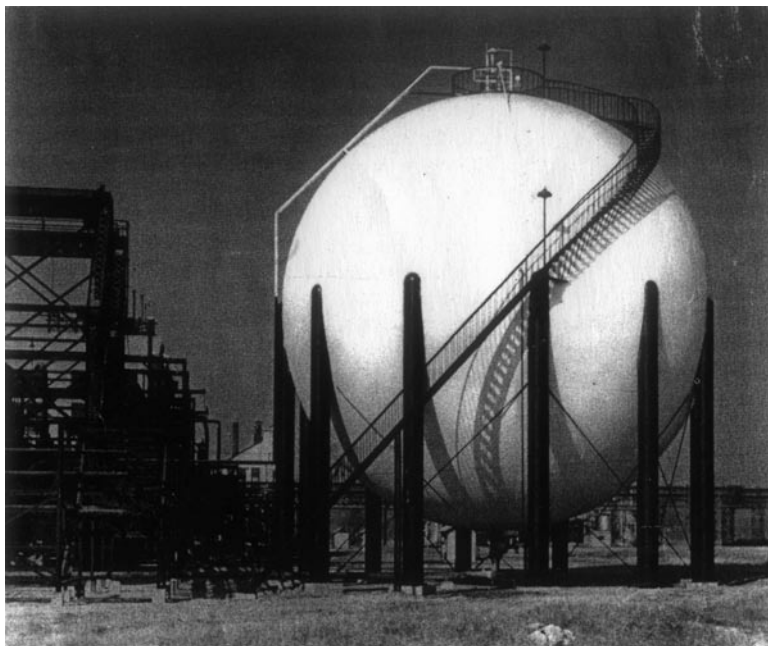
Brief 13 Ammonia synthesis yields using the Haber–Bosch process

Instead of “chemo-packing” hydrogen with nitrogen from air to make it more portable, one might consider reacting it with CO₂ from the air to form propane (C₃H₈), butane (C₄H₁₀), or methane (CH₄), by driving the following reversible gaseous reactions to the right (Ref. II-11):



or





Brief 14 Typical ammonia storage tank

Of these, reaction (5.5) is easier (exothermic) to carry out under pressure than (5.6) which requires some input energy (endothermic). Reaction (5.5) for propane and a similar one for butane produce portable alkanes known as LPG (Liquid Petroleum Gas) which at atmospheric pressure are liquid below 231.1 K (-42.1°C) and 273 K (-0.6°C) respectively. Like ammonia they can be kept liquid at room temperature (300 K) under a modest over-pressure between 5 and 10 atm. Methane on the other hand must be compressed to ~ 67 atm at room temperature or be liquefied at 111 K to be usable for automotive transport. Note that only 30% of the incoming hydrogen (H_2) in (5.5) is converted into propane. Reactions (5.5) and (5.6) are carbon neutral and product fuels are “green” since combustion of these fuels puts the same amount of CO_2 back into the atmosphere as was taken in during their manufacture.

While reaction (5.5) for synthesizing higher alkanes from hydrogen and atmospheric carbon dioxide might be technically feasible, compared to ammonia synthesis (5.4) the problem is that the concentration of carbon dioxide (CO_2) in the air is only 0.03% compared to 78% for nitrogen (N_2). This means one has to compress a lot of air to extract enough CO_2 before introducing it into the reaction vessel for reaction (5.5). It amounts to moving 2,600 times more air (requiring compression energy) than for extracting nitrogen from air to carry out reaction (5.4). Assuming the US has 100 nuclear power plants making petrol-replacing ammonia synfuel in 2050, a very coarse calculation shows that each plant would need to process about 3×10^6 L/s of air. At a pump-energy cost of 100 J/L this requires 300 MW ($= 100$ MWe) of air-processing power for each plant. If instead of ammonia, one would extract CO_2 from the air to

make propane via (5.5), one would need $2,600 \times 3 \times 100 \text{ MWe} = 780,000 \text{ MWe}$ for air collection at each plant. This is impossible if each plant only generates between 1,000 and 3,000 MWe. Except from air, any other source of CO_2 would not be carbon neutral. Taking CO_2 (or C) from vegetation for (5.5) is not as efficient as extracting bio-alcohol from them. Which portable synfuel is most practical to mass-produce when oil is gone will depend not only on production costs of course, but also on engine performance, ease of synfuel distribution, and safety when used for public transportation vehicles. Note that distribution systems for both ammonia and propane are already in place: liquid anhydrous ammonia is widely used in agriculture, while liquid propane (and butane) is distributed globally as LPG (Liquefied Petroleum Gas). While propane manufacture from coal via the Fischer–Tropsch process may be viable and necessary for an interim period until enough prime nuclear power is installed, because of the paucity of atmospheric CO_2 , it seems that only ammonia synfuel made via (5.4) is practical for the long term to replace petroleum fuels.

The list of feasible near- and far-future synthetic fuels or “synfuels” made with inputs of (nuclear) heat or electricity, water, air, and coal may be summarized as follows:

Hydrogen (H_2).

Ammonia (NH_3) and hydrazine (N_2H_4).

Syn-alkanes (C_mH_n), methane (CH_4), propane (C_3H_8), butane (C_4H_{10}).

Bioorganic Ethanol ($\text{C}_2\text{H}_5\text{OH}$), methanol (CH_3OH), biodiesel ($\text{C}_m\text{H}_n\text{O}_k$).

Syn-petrols ($\text{C}_m\text{H}_n\text{O}_k$), acetylene (C_2H_2), etc.

Brief 15 shows key combustion properties and fuel tank storage features (volume) of these synfuels some of which may be used in future public transportation.

From the analysis given earlier, for each GJ of heat expended in synfuel manufacture, between 0.1 and 0.6 GJ can be stored as portable chemical energy for the generation of electro-mechanical motion by an ICE or FCE. When consumed, hydrogen, ammonia, hydrazine, and bio-alcohols discussed above return the same chemical species used in their manufacture back to the biosphere. Their reaction chemistries in ICEs or FCEs reverse the synthesis steps and thus are “green”. Only the coal-derived syn-petrols would add new globe-warming CO_2 to the atmosphere. The limitations on carbon-bearing biofuels is the enormous acreage needed for their cultivation, while making green butane and propane synfuels using atmospheric carbon dioxide is impractical because of the prohibitively low CO_2 concentration in the biosphere. This makes ammonia (and less so hydrogen) the most attractive synfuel for long-term replacement of petroleum fuels.

To satisfy world demand for making portable synfuels when oil is gone and to avoid global warming, one finds that only heat or electricity from uranium fission plants can economically produce the large quantities needed for extended periods (Chapter 3). Nuclear fission of uranium and thorium is able to support all synfuel production for more than 3,000 years for the entire world. Proposed “renewable” solar and wind energy sources can not provide sufficient capacity at a reasonable and affordable cost. Geothermal steam may be added to the world’s supply of electric energy for a while. But it is only available at a few locations on earth in limited quantity, facing exhaustion after a few decades. Nuclear power plants on the other hand can be constructed anywhere and can provide heat energy for millennia at a 1,000

Brief 15. Fuel combustion properties and storage features.

Fuel	Heat of combustion (kJ/kg)	Vapor ignition temperature in air at 1 atm	Flammability range in air (mole %)	Density @ 25°C, 1 atm (kg/m ³)	Fuel tank with 2.2 GJ = 0.72 GJ(m) of Latent energy	
					Amount (kg)/(lb)	Volume (L)/(gal)
Gasoline (ℓ) (C ₈ H ₁₈)	48,187	~500°C	1–8%	737.38	46/101	62.5/16.5
Alcohol (ℓ) (C ₂ H ₅ OH)	27,000	~600°C	3–19%	795.24	82/181	107/28.3
Ammonia (ℓ) (NH ₃)	22,550	651°C	15–28%	682.8 (12 atm)	98/216	143/37.9
Propane (ℓ) (C ₃ H ₈)	45,976	468°C	2.2–9.5%	500.5 (8.5 atm)	97/210	194/51.2
Butane (ℓ) (C ₄ H ₁₀)	45,339	430°C	1.8–8.4%	578.8 (3 atm)	49/107	85/23
Hydrogen (ℓ) (H ₂)	125,000	580°C	4–77%	67.5	18/40	262/69
Methane (g) (CH ₄)	50,144	537°C	5–15.4%	0.7174(g)	42/93	58,543(g) /15,466(g)
Hydrogen (g) (H ₂)	125,000	580°C	4–77%	0.0899(g)	18 / 40	200,216(g) /52,893(g)

1. An average (2005) passenger car carrying 2.2 GJ of portable fuel in its tank can move approximately 600 km (= 373 miles).
2. Volumes in the last column are at 25°C and 1 atm except for liquid ammonia, propane, and butane which are compressed; 1 US gal = 3.785 L; 1 m³ = 264.17 US gal; 1 kg = 2.2 lb; (ℓ) = liquid, (g) = gaseous.

times higher concentrations. In conclusion, most portable synfuels of the future will more than likely be synthesized by nuclear electricity or heat with air and water as feed. Some bio-alcohols may also be in the synfuel mix, while plastics and other hydrocarbon-based materials will be derived from coal using nuclear electricity.

Note finally that for a chemical rocket going into space where air is absent, it is necessary to provide two chemical reactants to produce heat and thrust. That is, both an oxidizer such as liquid oxygen or peroxide and a fuel like liquid hydrogen or hydrazine must be carried by a chemical rocket to propel it. On the other hand fission-heated nuclear rockets only need hydrogen. Auxiliary power systems on space vehicles likewise can not depend on atmospheric oxygen. Unless there is adequate exposure to the sun to energize some solar cells, nuclear decay heat is provided by a reactor-produced radioisotope like californium-252 (Cf-252).

5.1.2 Electric Storage Batteries

While electric-grid energy can not be conveniently carried along by a vehicle unless electricity-carrying guide-wires or rails contact it continuously as is done for trains, trams, and city buses equipped with contact blades, it is possible to deposit electric energy in portable storage batteries to power automobiles. Unfortunately energy/

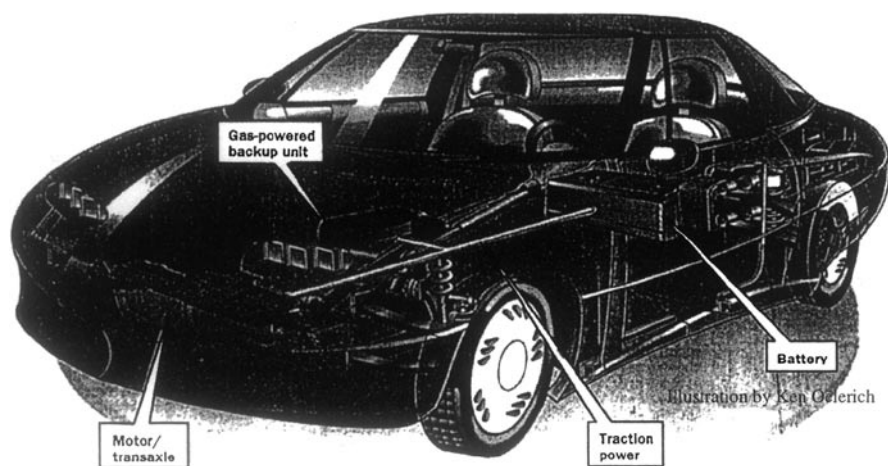
weight ratios of the lightest known storage batteries are rather low, making it impractical for them to compete with present automobile combustion engines that are fueled with petrol. Only for special situations like wheelchairs, golf-carts, and short-distance (urban) vehicle transportation with 100 km (60 miles) ranges, are electric storage batteries useful.

In 1995 the State of California demanded that the automobile industry produce some electric cars by 1998 to combat air pollution. So a number of electric cars powered by stacks of batteries were built. Batteries can store electric energy from the electric power grid and if they are rechargeable, they can serve as clean non-polluting portable energy carriers. The results over the past decade have not been promising however. The best purely electric models developed by GM, Chrysler, Nissan, and other car makers (Ford produced a hybrid later – see below) carry 200–500 kg of battery weight, and typically have a maximum range of 100 km (60 miles), while requiring 3–6 h of battery recharging time. Rechargeability features of existing (lead acid) batteries and their power and energy capacity per unit weight have been improved somewhat, but driving ranges for these electric cars are still far below those of modern petrol-fueled automobiles. Typically electric cars are operated at 300–330 V, with outputs of 250 W/kg fully charged dropping to 100 W/kg at 80% discharged, and capacities of 32 Wh(e)/kg for standard lead-acid units. For newer lighter glass-fiber reinforced lead-acid batteries, these numbers were improved to 500 W/kg (full) → 240 W/kg (80%) and 42 Wh(e)/kg. Later models using nickel metal hydride (NiMH) and zinc-bromine-based batteries claim 75 Wh(e)/kg and possible ranges of 250 km (156 miles), while new lithium polymer and lithium-manganese dioxide systems (LiMnO_2 , LiMn_2O_4) have yields of 200 Wh(e)/kg and a potential 350 km (219 miles) range. The very latest (2009) lithium-manganese high-capacity battery developed at the Argonne National Lab now claims about 660 Wh(e)/kg or 2.4 MJ/kg at 4.3 V (average 3.7 V). Using our standard $0.7 \text{ GJ(e)} = 200,000 \text{ Wh(e)}$ to move a car 600 km (373 miles), the latest of these batteries with 660 Wh(e)/kg, would require 303 kg (667 lb) of minimum weight for such a range or about 450 kg (1,000 lb) packaged. This is equivalent to the weight of six human passengers! With possible maximum technically achievable improvements of future engine efficiencies such that only 0.5 GJ(e) can move a car 600 km, the needed packed lithium battery weight might be lowered to 320 kg (708 lb) equal to about four human passengers.

The difficulty with storage batteries is that nature has a more or less fixed electron density per unit mass for chemical compounds and the useful available energies from electrochemical interactions are only on the order of 1 eV.² Combustion yields 10–100 times more energy per unit weight of fuel than what is retrievable from a compound in an electrochemical reaction, although only one third of combustion heat can be converted into electro-mechanical energy. Typically a tankful of petrol for a medium-sized automobile contains 60 L (16 gal), and weighs 44.5 kg (98 lb) for a driving range of 600 km (373 miles). Substituting this fuel weight with 450 kg (1,000 lb) or even 320 kg (708 lb) of batteries is clearly unattractive as long as there is petrol or an alternative synfuel.

²The microscopic energy unit of eV (electron-volt) is most commonly used in physics for energy exchanges between single atoms and molecules. $1 \text{ eV} = 1.6021 \times 10^{-19} \text{ J}$.

While electric storage batteries can not compete with the internal combustion engine (ICE) in power per unit weight, in recently introduced “hybrid” cars, a combination of both has been achieved (see Brief 16). For long-distance driving the ICE runs the car, while in stop-and-go city driving a 100 kg (220 lb) electric storage battery kicks in and moves it. The ICE recharges the battery when it is low. By our estimates a 100 kg latest-model lithium car battery could take a car 187 km or 117 miles without recharging. A hybrid car still produces globe-warming CO_2 of course, but less than a conventional ICE automobile. FCEs also depend on electro-chemistry, but have the advantage that oxidant (O_2) is supplied by air and waste product water (H_2O) is exhausted to air. Their fuels are light and thus they give better driving ranges than electric storage batteries could provide on one charge. Besides lower weights, FCEs also don’t require frequent recharging. For this reason development of “electric” cars have been focusing on fuel-cell engines (Section 5.2.2). The details of battery and fuel-cell physics can be found in Refs. III-1 and III-2.



Brief 16 Hybrid electric/ICE powered car

5.1.3 Flywheel Energy Storage (Mechanical Batteries)

Using induction coils, a possible portable energy storage scheme is to convert electric energy into mechanical energy of a high-speed rotating flywheel, and vice versa. This is sometimes referred to as a “mechanical battery” and is used on some city buses, for example in Switzerland. It has also been considered for automobiles. However to store sufficient rotational energy for moving a car 600 km (373 miles) before a recharge, requires more than 1,000 kg of flywheels. This is with assistance of fibers with the highest-known tensile-strength to hold spinning flywheels together.

An electro-dynamic flywheel device or “mechanical battery” is a non-polluting energy storage unit which could be charged up in everyone’s garage by electricity from

the power grid. In such a direct electricity-to-electricity energy transfer between utility power and a portable non-chemical electric storage device, there is no need for intermediate conversions to chemical or electrochemical storage systems. In the flywheel scheme, counter-rotating pairs of magnetically suspended discs or tori are spinning at 180,000 rpm in evacuated cylinders as shown in Brief 17. They are electromagnetically coupled to induction coils that can extract electric energy or, in reverse, can store electric coil energy as mechanical energy of rotation into the spinning discs. As with electric storage batteries, one finds that engine weight is again a problem maker. The quantity of rotational energy stored in a flywheel is given by:

$$E = \frac{1}{2} \langle M \rangle (\Omega R)^2 = \frac{1}{2} \langle M \rangle V_a^2, \text{ Joules(e)} \quad (5.7)$$

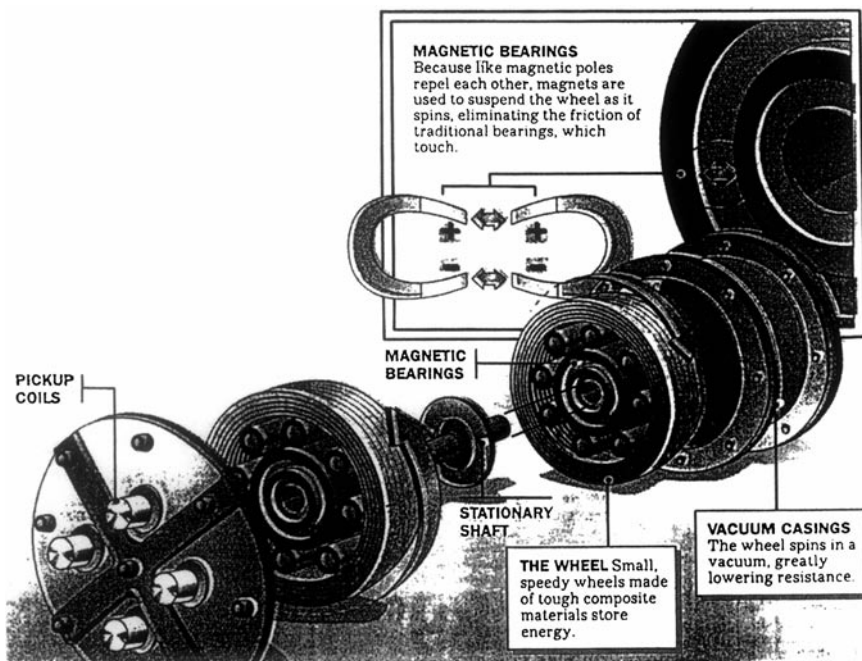
Here Ω , V_a , and R are respectively the rotational velocity (rad/s), circumferential velocity (m/s), and outer radius (m), while $\langle M \rangle$ is the effective weighted mass (kg) of the rotating flywheel. For a torus-shaped (doughnut) flywheel with a thin body cross-section whose mass resides mostly at radius R , the mass $\langle M \rangle = M_{\text{torus}}$, while for a solid disc flywheel with distributed mass, $\langle M \rangle = \frac{1}{2} M_{\text{disc}}$. From Eq. 5.7 it is clear that the highest tolerable circumferential velocity gives the highest stored flywheel energy. An analysis of centrifugal forces shows that the maximum tolerable value for V_a is:

$$V_m = (V_a)_{\text{max}} = (\Omega R)_{\text{max}} = (\sigma / \rho)^{1/2} \text{ m/s} \quad (5.8)$$

Here σ is the tensile strength (N/m²) and ρ is the density of the rotating material (kg/m³). A fiber material which is believed to have the highest tensile strength is spider-silk. It was reported recently that spider-silk fiber molecules can be extracted from goat's milk. With a spider-silk fiber skin confining a heavy material, we estimate the maximum allowed V_m value is $V_m \approx 800$ m/s. If we assume our "standard" 0.72 GJe of energy is to be stored in a flywheel to achieve a 600 km (373 miles) range, one calculates from Eq. 5.7 with $E = 7 \times 10^8$ J(e) and $V_m \approx 800$ m/s, that $\langle M \rangle = M_{\text{torus}} = 2,180$ kg (4,818 lb)! This mass could be distributed over 48 tori at 46 kg per torus, who are spinning inside 24 evacuated cylindrical chambers, each containing two counter-rotating tori.

Spinning at 180,000 rpm $\approx 10^4$ rad/s and with $V_m = 800$ m/s, one finds from Eq. 5.8 that the discs or tori must have $R = 0.08$ m = 8 cm or an outer diameter of $D = 2R = 16$ cm. Such an outer diameter is reasonable for cylinders that must fit under the hood of an automobile. This result is independent of torus or disc mass. A lower rpm will increase the value of D if V_m is fixed. With a torus of 8 cm outer radius and a torus body cross-section of S cm², the torus body volume equals $Q_{\text{torus}} = 2\pi RS = 50.27 S$ cm³. Thus if each torus mass is 46 kg = 46,000 g, the density of the fiber-encapsulated material would have to be $\rho = 46,000/Q_{\text{torus}} = 915 S$ g/cm³. Using depleted uranium with $\rho = 18$ g/cm³, one finds that S must equal $S = 51$ cm² for each torus. This could be achieved if the uranium torus bodies had a circular cross-section with body diameter $D_b = 8$ cm or a rectangular cross-section with a width of 3 cm and height of 17 cm. Instead of 2,180 kg (4,818 lb), a more reasonable

total flywheel mass would be $\langle M \rangle = 400 \text{ kg}$ (881 lb), giving a driving range of 107 km or 67 miles. Assuming again 48 tori, each now carrying 8.33 kg of depleted uranium, one finds $S = 9.2 \text{ cm}^2$ in this case. This requires a torus body diameter of $D_b = 3.42 \text{ cm}$ if the cross-section is circular, or $2 \times 4.6 \text{ cm}$ for a rectangular cross-section. An 8.33 kg torus body is more convenient than a 46 kg torus body, but the driving range is of course only 107 km (67 miles) now.



Brief 17 Flywheel battery components

Development of flywheel-powered automobile engines clearly depends on the availability of high-tensile-strength fiber materials such as spider-silk which can withstand high stresses at high velocities V_m to prevent flywheel disintegration. It is unlikely that the weight problem can be overcome since it is improbable that a super-material exists which can double the highest estimate of $V_m = 800 \text{ m/s}$. Satisfactory solutions must also be found to minimize damage produced in auto crashes, in which stored rotational energy is suddenly released and converted into random kinetic energy. Using adjacent counter-rotating discs can partially neutralize such released energies. In addition, energy absorbing or deflecting skirts to minimize damage in case of an accident need to be explored and tested. Fires from a bursting gas/petrol tank in today's auto crashes can of course release as much energy in the form of heat, and are just as destructive.

A Chrysler-sponsored experimental flywheel-powered automobile at the 1994 Los Angeles auto show had a reported twenty cylinders under the hood, each cylinder

containing two counter-rotating discs spinning at 200,000 rpm. It was reported to develop $100 \text{ kW(e)} = 134 \text{ hp}$ of mechanical power at start-up and to have a range of some 320 km (200 miles). By the estimates given above, such a range would require about 1,000 kg (2,200 lb) of flywheel mass if $V_m = 800 \text{ m/s}$. Instead of fully fly-wheel-powered cars, hybrid systems might be explored. Like electric hybrids, an ICE could in principle be used for long-distance driving and flywheels for short trips. But in summary, mechanical flywheel batteries do not offer much improvement over electric storage batteries even with use of the highest tensile-strength materials.

5.2 Vehicle Propulsion Engines

Besides well-developed electric motors empowered by electric or mechanical batteries, the three major prime movers which have been thoroughly investigated over the past 100 years, and which require portable combustible fuels are:

1. Internal combustion engines (ICEs)
2. Fuel cell engines (FCEs)
3. Steam engines

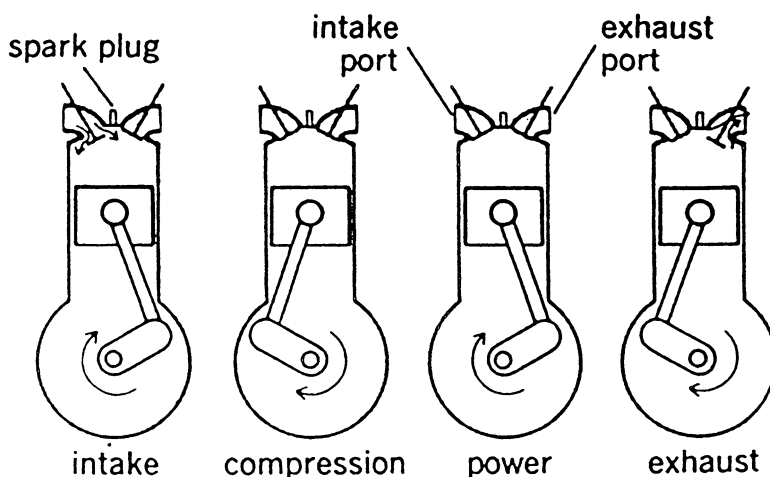
In what follows we shall briefly review these devices and examine their ability to consume future synfuels.

5.2.1 *Internal Combustion Engines (ICEs)*

The internal combustion engine (ICE) is the oldest device for propelling automobiles with portable petrol as energy source. It made its debut at the turn of the twentieth century. Coal-burning steam engines had preceded the ICE during the 1800s, so the concept of moving a piston back and forth guided by a cylinder using heated vapor or steam was not new. However coal was burnt separately to evaporate water in a boiler while in ICEs, burning fuel transfers heat directly to expanding gas and is incorporated in it. Although others had suggested it earlier, N.A. Otto is credited with building the first successful petrol-burning ICE in 1876, while G. Daimler first installed an ICE in an automobile in 1889 using suitable transmission gears to drive it.

In the ICE, a mixture of air and petrol is admitted and compressed in a cylinder provided with a moving reciprocating piston connected to a crankshaft that turns wheels or gears. As the piston compresses the mixture in the closed cylinder, the latter is ignited by a spark at the highest compression point just before the piston reverses its travel (see Brief 18). The heat of combustion then expands the gas which pushes the piston back in reverse which in turn rotates the crankshaft. After this work stroke, the expanded combustion gases are exhausted and

a fresh mixture of air and petrol is injected to repeat the cycle. Many ingenious improvements to this basic concept were made during the 1900s, resulting in the sophisticated multi-cylinder automobile engines used today. The aircraft jet engine developed in the 1950s in England also burns a petrol derivative, aviation kerosene, which is mixed with air in a confined internal space and ignited. But instead of moving pistons, it utilizes expansion of the hot gases directly for propulsion.



Brief 18 Illustration of internal combustion engine four-stroke cycle

Three main types of refined oil are produced to fuel present-day ICEs, namely automobile petrol, diesel, and aviation fuel. Petrol-burning ICEs use spark-plugs to ignite combustion, while diesel-burning engines self-ignite when compression temperatures and pressures reach a certain point. The hydrocarbon composition of diesel fuel is therefore different from that of petrol. Both petrol and diesel are obtained from crude oil but from different refinery distillate fractions.

Although other means of locomotion will be developed when oil reserves are depleted, the ICE has been such a success during a whole century of development and usage that it probably will not be totally abandoned. While today's ICEs run on petrol or diesel there is no reason other oxygen-burning synfuels can not replace them to provide expansion heat. Alcohol (C_2H_5OH), ammonia (NH_3), hydrazine (N_2H_4), and pure hydrogen (H_2) all burn and react with oxygen (O_2) from air at certain ignition temperatures and mixing ratios. In fact alcohol and ammonia-burning ICEs have been built and tested, while hydrazine and hydrogen have fueled rocket engines for decades. Even though the US DOT (Dept of Transportation) has labeled ammonia as non-flammable, ammonia/air mixtures can be ignited at $780^\circ C$, burning with a yellow flame that yields nitrogen and water vapor. Mixtures of 16–25% ammonia gas in air can explode (Refs. II-12, III-3) if ignited. Of course existing ICEs must be modified, since each synfuel has a different ignition point

and requires different high-temperature containment materials. All hydrocarbon and alcohol-fueled ICEs produce unwelcome globe-warming carbon dioxide (CO_2) gas besides water vapor (H_2O). However the CO_2 exhausts from bio-alcohols are balanced by atmospheric CO_2 absorbed during plant growth. In addition, regardless of the fuel, high temperatures in ICE's produce some NO_x gases since both nitrogen (N_2) and oxygen (O_2) reside in air intakes. At the high temperatures during combustion they can react with each other to form NO_x gases. For ammonia (NH_3) and hydrazine (N_2H_4) that are burnt in an ICE, NO_x byproducts might be somewhat higher. Nitrogen and water vapor can be the main exhausts however if NO_x -removing catalytic converters developed for petrol-burning automobiles are used in future synfuel-burning ICEs.

As discussed in [Section 5.1.1](#), synfuels will have to be manufactured in large quantities using electric energy or heat supplied by nuclear and/or coal power plants when petroleum fuels are no longer available. For the large numbers of long-haul vehicles used in ground transportation all over the world, the use of non-polluting hydrogen- or ammonia-consuming engines appear to be the best solution to reduce future global warming when oil runs out. For aircraft propulsion where compact power systems are essential, it may be more efficient to use hydrazine-burning fuels and modified jet engines if handling and storing of hydrazine can be done safely and NO_x byproduct exhausts can be eliminated.

5.2.2 *Electrochemical Fuel-Cell Engines (FCEs)*

In a fuel-cell, chemical energy is directly converted into DC electric energy (see Brief 19a and Refs. III-1 and III-2). In automobile applications, the DC voltage of about 1 V per cell is boosted by a stack of cells in series to about 120–330 V to drive four electric motors placed on each wheel or to run one motor and engage a gear-train that moves the car. Electrically driven automobiles have been under development for many decades and several well-tested schemes are available. The first publication of experiments with H_2/O_2 fuel-cells was by Sir William Grove in 1839 in England. Later at the turn of the nineteenth century (1896), W.W. Jaques in the US and W. Ostwald in Germany, reported successful direct electricity generation with high-temperature (500°C) carbon/air fuel cells. However interest in direct carbon/air fuel-cell generation of electricity waned, when more robust coal-burning steam turbines showed successful conversion of heat to electricity at about the same time. Renewed efforts to produce electric power on a smaller scale with H_2/O_2 fuel-cells using modern materials, were started by Francis T. Bacon in 1933. After him, numerous other fuel-cell studies were undertaken by research teams all over the world. Several fuel-cell units with 2–20 kW(e) outputs were developed and used by NASA on Gemini, Apollo, and other spacecraft missions in the 1970s and thereafter. Brief 19b–19d show some early fuel-cell systems developed for NASA.

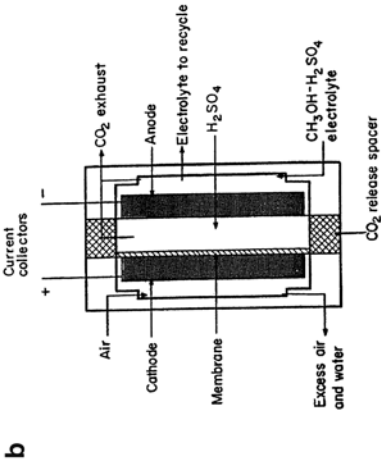
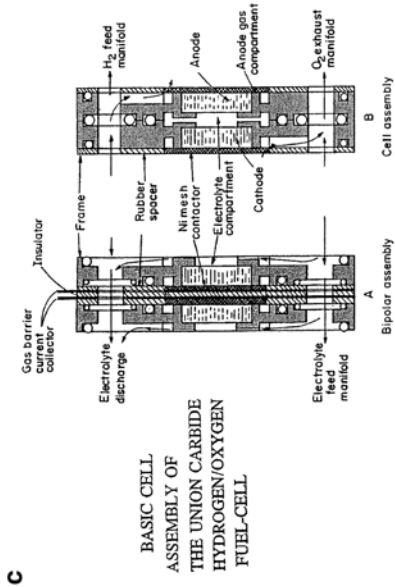
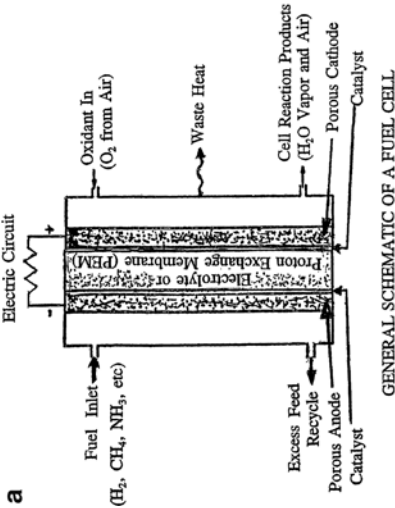
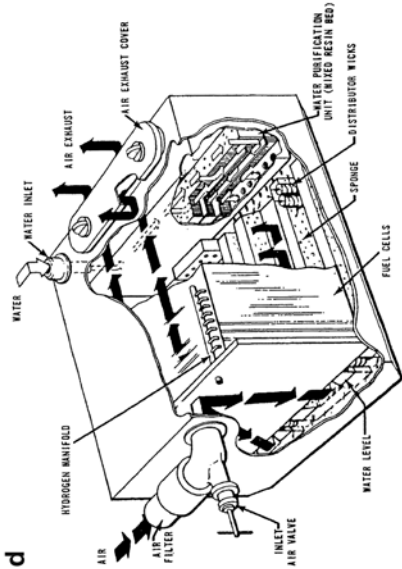


DIAGRAM OF A SINGLE UNIT OF ESSO'S METHANOL FUEL CELL

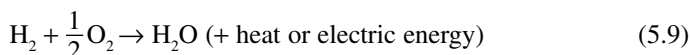


GENERAL ELECTRIC 200-WATT FUEL-CELL POWER PACK

Brief 19 Typical fuel cell systems

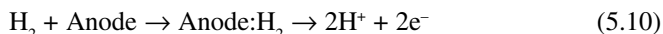
The fuel-cell is similar to an electric battery except the active agents are gases, usually air or oxygen (O_2) as “oxidant” and hydrogen (H_2) as “fuel”, each being continuously supplied to one of two electrodes separated by an electrolyte or proton exchange membrane (PEM). Solid PEM’s are preferred today over liquid (corrosive) electrolytes used in earlier devices. The fuel-cell process is inherently more efficient than a chemical reaction in a combustion engine where heat is produced first and then converted into mechanical motion. The latter conversion has a typical efficiency of about 33% set by thermodynamics which rules heat conversions. Fuel cells are 45–85% efficient in practice, losses being ruled by the kinetics in electrodes and electrolytes or PEM’s.

Hydrogen and oxygen gases when mixed would like to react and form water by the overall reaction:

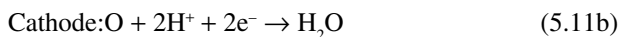


The reason is that the chemical binding of atoms in H_2O is stronger than that in H_2 and O_2 . But at room temperature, an “energy barrier” prevents them from undergoing reaction (5.9). There are two man-engineered pathways by which H_2 and O_2 can overcome the barrier and react to form H_2O . One is by igniting combustion and the other via inducing electrochemical action. The energy barrier in reaction (5.9) arises from the fact that the two H atoms in H_2 and the two O atoms in O_2 molecules are strongly bonded to each other. They must be taken apart first before they can recombine into H_2O . Because the total binding energies of H and O in H_2O are larger than the sum of the bond-breaking energies of H_2 and O_2 , the difference manifests itself as kinetic energy in the form of heated gas if ignited in an ICE, or as electron motion if catalyzed on electrodes in an FCE. In combustion, the heat increases the relative collision velocities of O_2 and H_2 molecules to the point that the bonds in H_2 and O_2 are broken, allowing for a re-arrangement of O and H atoms into H_2O . Kinetic energies required for prying O_2 and H_2 molecules apart into atoms and reforming them into H_2O molecules in collisions are on the order of 5 eV per molecule (see footnote 2). A gas mix of H_2 and O_2 will therefore not start to react measurably until an ignition temperature of about 580°C is established. Since liberated heat can keep the gas at 580°C, for example after igniting the reaction by an electric spark, reaction (5.9) becomes self-sustaining in an ICE.

In the electrochemical scheme, electrodes and electrolyte or a PEM are used to catalyze reaction (5.9) with liberation of electric energy. As shown in Brief 19a, H_2 gas is bubbled over a positive electrode called the “anode” which is in contact with an electrolyte or PEM (proton exchange membrane; proton = ionized H atom = H^+). The latter helps dissolve or dissociate H_2 to become ionized with energy expenditures of about 1 eV/molecule ($= 1.6021 \times 10^{-19}$ J/molecule):



Process (5.10) can proceed at a much lower temperature (70–150°C) than what is required in combustion. To get electrons to flow in an external circuit, O_2 is fed to a negative electrode or “cathode” placed on the other side of the electrolyte or PEM, where incoming H^+ ions are recombined with oxygen atoms O and electrons:



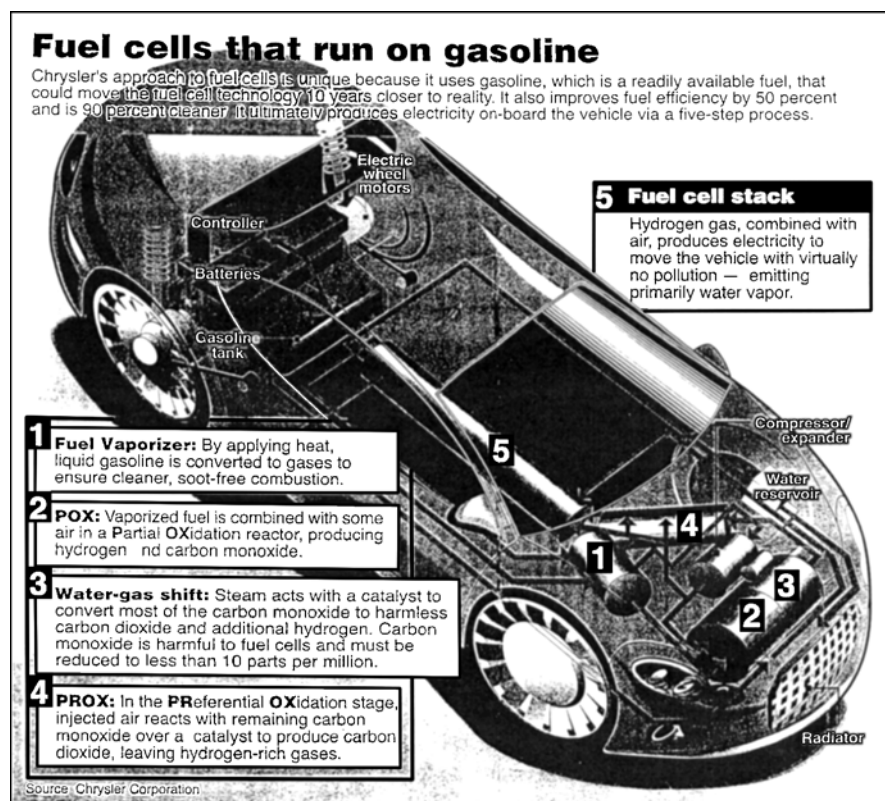
Electrons liberated on the anode by (5.10) travel through the outside power-delivering circuit to the cathode to be reunited with H^+ ions, making neutral H_2O molecules via (5.11b) in accord with overall reaction (5.9). Protonization of H_2 by electrolytes or PEMs in (5.10) lowers the energy barrier in (5.9). If the freed electrons in (5.10) are allowed to flow through a conducting wire to be reunited with H^+ on the cathode via reaction (5.11b) to form H_2O , they promote an electric current in the wire. Chemical energy is thus converted directly and efficiently into kinetic energy of electron flow, i.e. electricity. A little heat helps increase the proton flow through the electrolyte or PEM and thereby increases the electric current. Presently, Dupont's Nafion is the most popular PEM in experimental fuel-cells, but new high-temperature fluoropolymer materials are under development to improve PEM performance.

Hydrogen (H_2) is presently available as a cryogenic liquid or pressurized gas. An experimental fuel-cell car with ~100 kWe (~130 hp) of power has been reported to have traveled 400 km (250 miles) on a 155 kg (342 lb) tank with 10 kg (22 lb) of liquid H_2 . However liquid hydrogen is twice as expensive as gaseous hydrogen and various schemes are being investigated to compact it. Recent filament-wound high-pressure cylinders reportedly can hold 1 kg of H_2 each at 245 atm pressure. Each high-pressure fiber-glass cylinder weighs approximately 18 kg, has a storage volume of 50 L, and nominal outside dimensions of 25 D \times 125 L cm. For a 10 kg H_2 supply on board a car to travel 600 km = 373 miles (Brief 4), one thus needs ten cylinders. These cylinders could be mounted overhead or at floor-level in a car in two rows of five. They would occupy about ten times the space of today's 60-L petrol fuel tanks whose dimensions are typically 25 \times 40 \times 60 cm.

An alternative solution for gaseous hydrogen storage are H_2 -adsorbing porous "bladder" materials of light weight that compact H_2 in a volume a 1,000 times less than in its gaseous state. The adsorption energy for such storage must be moderate so that H_2 can be expelled from the bladder again with little heat, without destroying or incapacitating it. Bladder materials under investigation are clathrates, (mixed) metal hydrides like MgH_2 , LaNi_5H_6 , NaBH_4 , $\text{NaAlH}_4\cdot\text{Ti}$, and (mixed) amides such as LiNH_2 , LiN_aH_b , or $(\text{LiH})_m\cdot(\text{LiNH}_2)_n$. Various H_2 -adsorbing carbon and boronitride nano-tube configurations are also under investigation. A capacity of 8 wt% (kg hydrogen per kg bladder) with an adsorption energy of 15 MJ/kg H_2 or less is the goal. If 10 kg H_2 is the desired quantity (Brief 4) for one filling of a bladder fuel tank, such a fuel tank would weigh 125 kg without support structure. Presently the best materials still need improvements by a factor of 4 in weight as well as in adsorption performance to reach this goal. Note that hydrogen fuel storage costs extra energy, whether in bladder-heating to expel H_2 or in compressing/liquefying H_2 gas.

Instead of pure gaseous hydrogen (H_2), liquid petrol (C_mH_n), methanol (CH_3OH), and liquid ammonia (NH_3) at 12 atm or compressed (methane (CH_4) gas at 60 atm,

can be used as fuel in automobile FCEs. These fuels can be catalytically decomposed (“cracked”) with liberation of H_2 on the proton exchange membrane. Alloys of platinum, ruthenium, osmium, and iridium seem to give the best catalytic cracking performance. Although it adds complexity and cost to the FCE, it may be a more practical and safer solution to the hydrogen storage problem than the use of compressed hydrogen gas at 245 atm pressure or liquefied hydrogen at $T = 20\text{ K}$. Brief 20 shows an experimental car under development by Chrysler which uses a petrol-fed hydrogen-cracking fuel-cell engine. Such pioneers of the envisioned hydrogen age allow commercial development of fuel-cell technologies well before country-wide hydrogen (or ammonia) fueling stations and improved hydrogen storage techniques (or ammonia tanks) become available at a later date. Even though they still consume carbonaceous fuels and release CO_2 , less air pollution (no NO_x) is generated by FCEs than by ICEs, because of the lower operating temperature of fuel cells. This should please both environmentalists and futurists. Ultimately instead of cracked petrol, non-polluting pure hydrogen or ammonia would be the most desirable green fuel after oil runs out.



Brief 20 Fuel-cell-powered hybrid car

Besides the hydrogen tank storage problem, a second problem that has plagued fuel-cell systems is the fouling of electrodes and PEM's with particles and other "poisons". To minimize this difficulty requires careful filtering of the fuel. Additional schemes to cleanse electrodes and PEM's may involve intermittent ultrasonic exposures, intermittent "flushing" with AC currents, or intermittent laser beam illuminations. It has been suggested this could be carried out at fueling stations or in car owner's garages when the fuel-cell engine is not running (e.g. at night). PEM's could also be made replaceable like the sparkplugs on IC engines if their cost is not too high.

While rechargeable batteries and plug-in vehicle will most likely replace present automobiles for short-haul (e.g. urban) driving less than 100 km, for long-haul transport (e.g. trucking), hydrogen- or ammonia-fueled FCEs may eventually replace ICEs if present developmental problems can be solved and their inherently higher efficiencies can be maintained. Future development programs and tests might also determine whether fuel-cells can provide sufficiently compact take-off power to match the power from today's jet engines of large commercial aircraft.

5.2.3 *Steam Engines*

For completeness, we mention one of the oldest automotive devices, namely the steam engine powered by burning portable coal lumps as fuel. A return to using coal-burning steam-powered locomotives and automobiles of the 1800s has been proposed to counter the no-oil peril we face. Several experimental steam automobiles using modern components were built and tested in the 1970s, but further development was abandoned. Instead of burning dusty air-polluting coal, one could burn a liquid carbon-carrying synfuel (e.g. alcohol) to generate steam and propulsion. However in that case it is more efficient to burn the synfuel directly in an internal combustion engine than to use steam as an intermediary. Of course if coal-burning is forbidden to avoid global warming, the re-introduction of coal-fired steam engines to propel our automobiles would not be an option at all.